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The Role of Transverse Flow in Co-Injection Resin Transfer Molding

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Abstract

A co-injection resin transfer molding (CIRTM) process has been developed at the U.S. Army Research Laboratory (ARL) in collaboration with the University of Delaware. It enables two or more resins to be simultaneously injected into a mold filled with a stationary fiber preform. This process allows for the manufacturing of cocured multilayer multiresin structures in a single processing step. A separation layer is used to provide resin compatibility during cure and to control resin mixing. In this study, scaling issues relating the role of transverse permeability in resin mixing are investigated. This report presents two different approaches taken to understand the causes of transverse flow and to quantify the amount of transverse flow. The first approach is a one-dimensional (1-D) model, which explains the important parameters that govern the flow in CIRTM. The second approach is based on an existing finite element code, which is modified to allow for the injection of multiple resins. The total amount of transverse flow was quantified using the finite element code. This research shows that he CIRTM process requires a totally impermeable separation layer if CIRTM is used to manufacture large parts and/or if the resins injected have significantly different viscosities.

Acknowledgments

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1. Background and Motivation

Several composites application require multiple layers each serving a specific task while being integrated together in a single structure. For example, lightweight composite armor (Figure 1) incorporates different layers of different materials, which serve as ballistic protection, structural reinforcements, fire smoke and toxicity barriers, and signature management, while being integrated together into a single structure. Currently, the manufacturing of these kind of multilayer structures takes place in multiple steps in which each layer is manufactured individually and then bonded to the others. This process is not cost effective, and the secondary bonding procedures can introduce a number of defects into the final part. Pike, McArthur, and Schade [1] have shown that vacuum-assisted resin transfer molding (VARTM) processes can introduce significant cost savings, but they have been limited to a single resin system.

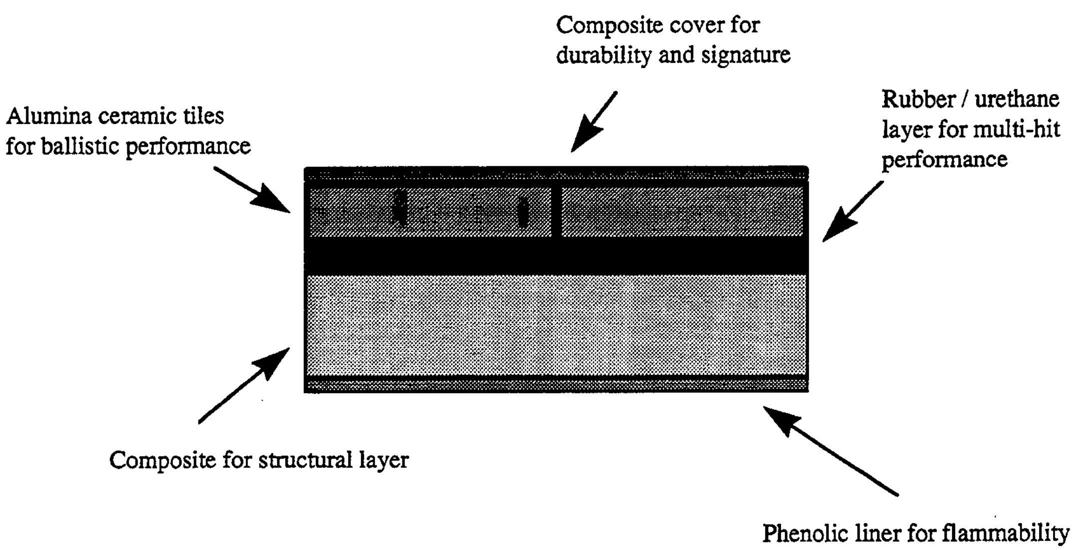

Figure 1. Cross Section of Integral Armor.

Co-injection resin transfer molding (CIRTM) is a new process developed by the U.S. Army Research Laboratory (ARL) and the University of Delaware that enables the manufacturing of multilayer hybrid structures in a single processing step [2]. CIRTM takes advantage of the unique properties and the cost effectiveness of existing liquid molding processes and improves

them by reducing the number of steps necessary to manufacture multilayer structures. Gillio [3] and Gillio et al. [4] give a complete overview of the co-injection process.

The applications of this process are not limited to integral armor. A number of applications exist for multilayer structures in which a thick structural layer of vinyl ester or polyester is combined with a thin layer of phenolic resin for fire, smoke, and toxicity protection. These applications include navy ship decks, containers to transport goods, rail cars, and anywhere composites want to be applied where flammability of materials is of concern.

2. One-Dimensional (1-D) Model

A simplified schematic of the co-injection setup is shown in Figure 2. In the majority of cases, the flow of a polymer inside a mold filled with a stationary fiber bed is modeled using Darcy's law [5]. The macroscopic velocity, u, is given by

$$u = \frac{\kappa}{\mu}\frac{dP}{dx}, \tag{1}$$

where κ is the permeability of the fiber preform, and μ is the viscosity of the resin. In co-injection, the top and the bottom preforms can have different permeabilities and the resins injected can have different viscosities leading to different resin velocities between the top and the bottom halves of the mold. The injection is assumed to be at constant pressure since this is the case in the majority of VARTM processes.

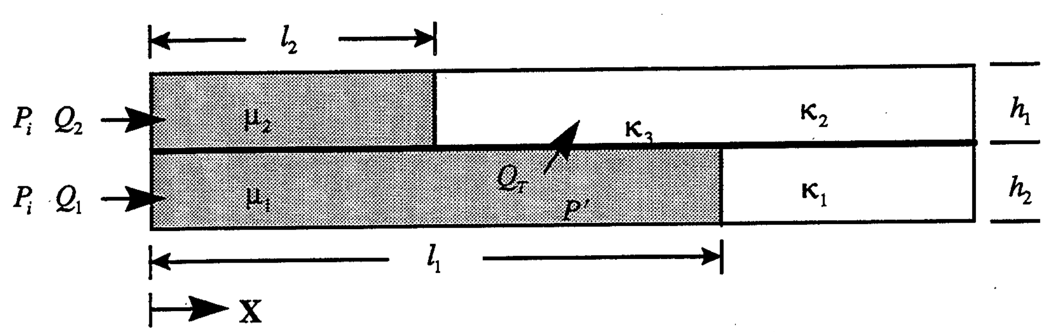

Figure 2. Schematic of 1-D Flow Model in CIRTM.

In such a case, the velocities of the two flow fronts is given by

$$u_1 = \frac{\kappa_1}{\mu_1}\frac{P_i}{l_1} \tag{2}$$

and

$$u_2 = \frac{\kappa_2}{\mu_2}\frac{P_i}{l_2}. \tag{3}$$

It follows that, if the ratios of permeability to viscosity are the same in both layers, the flow velocities will be the same. In most applications, this is not the case and one of the flow fronts will move ahead of the other.

As the flow moves through the mold, a pressure profile develops in both the top and the bottom halves of the mold. In the case where the cross flow between the two layers is small, these pressure profiles can be assumed to be linear. In this model, both pressure profiles are assumed to be linear. If the ratio of permeability to viscosity is different between the two layers, l_1 and l_2 will be different and a pressure gradient will form between the top and the bottom halves of the mold. This pressure gradient will drive the transverse flow. The transverse flow will be given by

$$u_3 = \frac{2\kappa_3}{\mu_1}\frac{P'}{(h_1 + h_2)}, \tag{4}$$

where κ_3 is the transverse permeability of the middle layer, $(h_1 + h_2)/2$ is the distance between the midpoints of the two layers, and P' is the average pressure difference between the two layers. Since both pressure profiles are assumed to be linear, and recalling that the pressure is zero in front of the fluid front (i.e., where the preform is not impregnated), P' is given by

$$P' = \frac{P_i}{l_1}\frac{(l_1 - l_2)}{2}. \tag{5}$$

Here, the assumption has been made that the ratio of permeability to viscosity of layer one is greater than that of layer two. Substituting equation (5) into equation (4), an equation for the cross flow is obtained as a function of the inlet pressure and the position of the flow fronts:

$$u_3 = \frac{\kappa_3}{\mu_1} \frac{P_i (l_1 - l_2)}{l_1 (h_1 + h_2)}. \tag{6}$$

In equation (4) and (6), the viscosity of fluid one was used, assuming that the ratio of permeability to viscosity of layer one is greater than that of layer two, which is the case in Figure 2. Equation (6) can be verified in the extreme cases: if the transverse permeability is zero, the transverse flow is zero; if the two flow fronts are at the same location (i.e., $l_1 = l_2$), there is no pressure gradient and the transverse flow is zero. A mass balance yields

$$Q_1 - Q_T = Q_2 + Q_T, \tag{7}$$

where Q_1 and Q_2 are the flow rates through injection gates one and two, respectively, and Q_T is the flow rate through the separation layer. Assuming unit width of the part, the flow rates are given by

$$Q_1 = \frac{\kappa_1}{\mu_1} \frac{P_i}{l_1} h_1, \tag{8}$$

$$Q_2 = \frac{\kappa_2}{\mu_2} \frac{P_i}{l_2} h_2, \tag{9}$$

and

$$Q_T = \frac{\kappa_3}{\mu_1} \frac{P_i (l_1 - l_2)^2}{l_1 (h_1 + h_2)}. \tag{10}$$

Knowing the flow rates, it is possible to compute the flow progression in the x direction based on a given time step, *dt*. The positions of the two flow fronts can be obtained using the following expressions:

$$l_1 = l_1 + \frac{(Q_1 - Q_T) \cdot dt}{h_1 \cdot V_{f1}}, \tag{11}$$

and

$$l_2 = l_2 + \frac{(Q_2 + Q_T) \cdot dt}{h_2 \cdot V_{f2}}, \tag{12}$$

where V_{f1} and V_{f2} are the respective fiber volume fractions of each preform.

Clearly, from equations (2) and (3), the flow in the layer with the highest ratio of permeability to viscosity will be ahead. However, the distance between flow fronts will not increase continuously but, rather, it will slowly approach a steady-state scenario. The exact time, or position, at which this occurs depends on the total amount of transverse flow, which depends on a number of other factors such as the transverse permeability and the pressure gradient formed in the transverse direction. Figure 3 shows a plot of the distance between flow fronts vs. the flow front positions for a variety of different transverse permeabilities. All of the cases eventually reach steady state. It should be noted that the nondimensional ratio R was used in Figure 3 because it emphasizes the various parameters that affect the resin flow. However, in this graph, only the transverse permeability was changed.

This behavior can also be observed in the equations. Substituting equations (8), (9), and (10) into equation (7) and assuming the two layers have the same thickness, h, and the fluids the same viscosity, the distance between the two flow fronts, normalized by the thickness, is given by

$$\frac{l_1 - l_2}{h} = -\frac{\kappa_2 h}{2 l_2 \kappa_3} + \frac{1}{2}\sqrt{\left(\frac{\kappa_2 h}{l_2 \kappa_3}\right)^2 + 4\frac{\kappa_1 - \kappa_2}{\kappa_3}}. \tag{13}$$

If the permeabilities of the two preforms are the same, the distance between the two flow fronts reduces to zero, as would be expected. Additionally, as l_2 becomes large, the distance between the two flow fronts becomes constant. Taking the limit of equation (13) as l_2 approaches infinity yields

$$\frac{l_1 - l_2}{h} = \sqrt{\frac{\kappa_1 - \kappa_2}{\kappa_3}}. \tag{14}$$

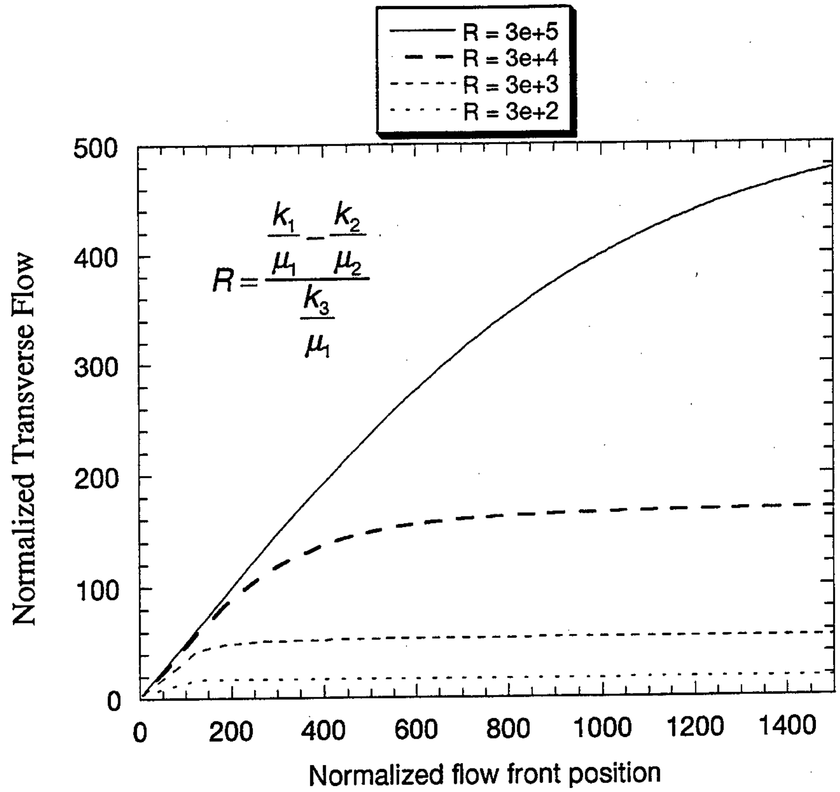

Figure 3. Effect of Transverse Permeability on Distance Between Flow Fronts in Top and Bottom Layers. All Variables Are Normalized With Respect to the Thickness of One Layer.

This equation was originally introduced by Bruschke [6].

The term under the square root on the right-hand side of equation (14) is exactly the same as the ratio R that was used in Figure 3, except that the viscosities were assumed to be the same and therefore they canceled out. The second important result that can be obtained from a simple 1-D model is the total amount of transverse flow. Figure 4 shows the effect of transverse permeability on the total amount of transverse flow. In this case, the permeabilities of the two layers were assumed to be the same, while the viscosity of one resin was four times that of the other. Under these conditions, different transverse permeabilities were used in an attempt to control the transverse flow. The trend observed is that the transverse flow increases rapidly in the initial stages of mold filling and, subsequently, when the distance between the flow fronts becomes constant, the total transverse flow does not increase significantly.

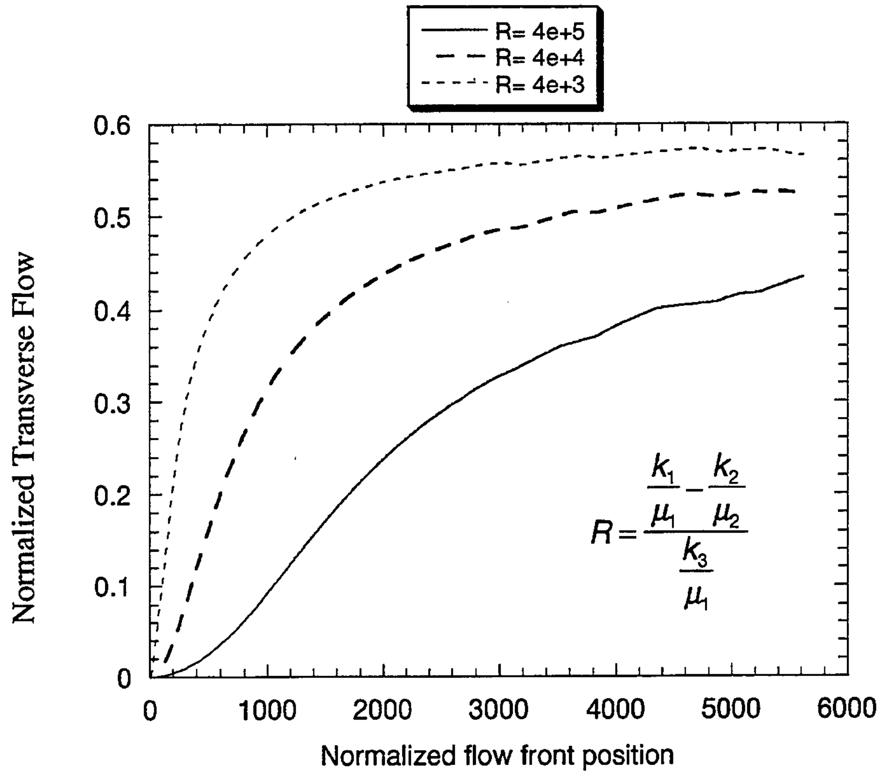

Figure 4. Total Transverse Flow as Percentage of Half of Mold Volume for Different Values of Transverse Permeability. The Flow Front Position Is Normalized With Respect to the Thickness of the Layer.

3. Finite Element Model

Liquid Injection Molding Simulation (LIMS) is a finite element code developed at the University of Delaware [7–12]. It is a two-dimensional (2-D) flow modeling package that can deal with complex geometries and multiple injection gates and vent locations. In traditional VARTM processes, the thickness is much smaller than the other two dimensions. The flow in the thickness direction can therefore be neglected, and a 2-D model can be used. However, this is not the case in CIRTM because the flow in the thickness direction plays an important role in determining the amount of mixing that takes place between the two resins.

In LIMS, the user creates the geometry of the part using a commercial finite element code. Once the geometry is created, it is converted into a file that is readable for LIMS. The user must then enter all of the material properties (i.e., resin viscosity, preform permeability, etc.) and the processing parameters (i.e., injection gates location, inlet pressure or flow rates, etc.). LIMS can then process all of this information and reproduce the pressure field in the mold, the filling history, etc. To simulate the co-injection process, the program was slightly modified. Only one type of resin can be injected into the mold using LIMS, but multiple injection gates are possible. Since the flow patterns are governed by the ratios of viscosity to permeability, the permeabilities in the top and the bottom layers were modified to account for the injection of resins with different viscosities.

The geometry used is shown in Figure 5, where the flow was modeled in the one and the three direction to be able to account for the transverse flow. LIMS is based on a control volume finite element approach [7]. It associates a control volume with every node in the finite element mesh (Figure 5) and, as the flow front moves, it assigns a fill factor to each node. If the control volume of a specific node is empty, the fill factor will be zero; if it is completely full, the fill factor will be one; and if it is partially full, the fill factor will reflect the percentage of the control volume that is filled. A script was written that calculates the volume of every node; it then uses the fill factors at each time step to determine how much fluid has entered the bottom half and the top half of the mold (Figure 5). These values are then compared to the amount of fluid injected through the two injection gates. The difference between fluid injected in one layer and volume filled in the same layer is computed, and this will be the transverse flow for this time step from mass conservation. Additionally, at every time step, the script compares the total fluid injected through both gates to the total volume filled in the two halves of the mold; the ratio of these two values should be one at every step. Finally, the accuracy of the results was checked by mesh refinement.

A parametric study was conducted on two parameters that the 1-D model had shown to be fundamental to understanding the transverse flow. These parameters were the transverse permeability of the separation layer and the total length of the part. The 1-D model emphasized

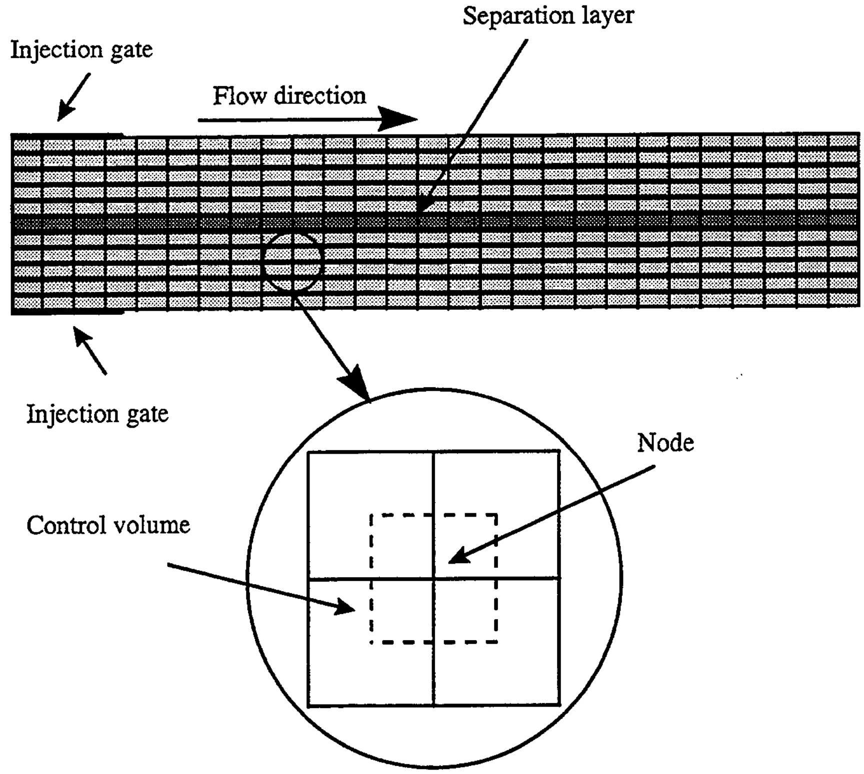

Figure 5. Schematic of Finite Element Mesh Used to Model Co-Injection Process.

other parameters, particularly the difference between the ratio of permeability to viscosity of the two layers. However, these values were maintained the same because, in a real world application, once the materials are selected, their properties vary only slightly.

4. Transverse Permeability

To better understand the role and importance of this parameter, a parametric study was conducted. The minimum transverse permeability was selected so that the total transverse flow would be less then 1% of half of the mold volume. The maximum transverse permeability was selected to be one order of magnitude greater then the in plane permeability. Figure 6 shows a comparison between the different transverse flows obtained. As expected, the transverse flow increases with decreasing transverse permeability (i.e., increasing R ratio). As before, the R ratio was used to emphasize all parameters that can effect the transverse flow. However,

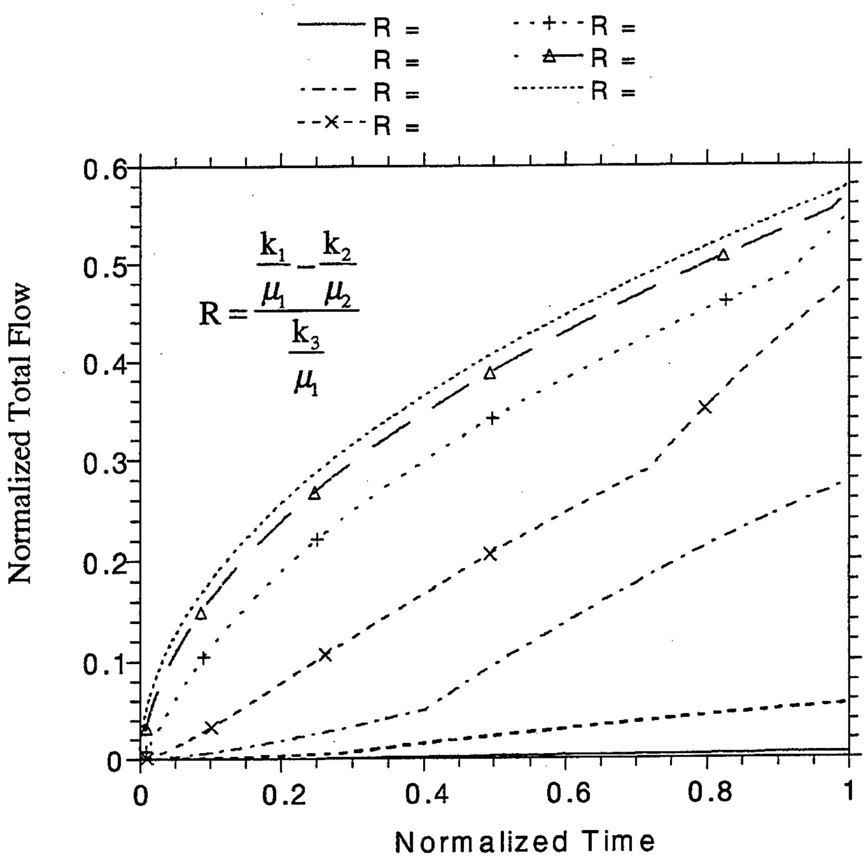

Figure 6. Total Transverse Flow for Different Transverse Permeabilities. Transverse Flow Is Normalized With Respect to Half of the Mold Volume. Time Is Normalized With Respect to Total Filling Time.

permeabilities and viscosities of the two layers were maintained constant. Additionally, the filling time decreases with increasing transverse flow. This happens because the maximum fill time is the time it would take the higher viscosity resin to fill its half of the mold without any cross flow. The transverse flow can be thought of as an additional inlet, so, as the transverse flow increases, it will take less time to fill the mold. One final behavior that should be observed is that the total transverse flow does not increase linearly with decreasing permeability. Figure 7 shows the total transverse flow as a function of transverse permeability. The transverse flow increases rapidly when the transverse permeability decreases from 6 orders of magnitude greater then the in plane permeability to 4 orders of magnitude. After this point, it slowly levels off.

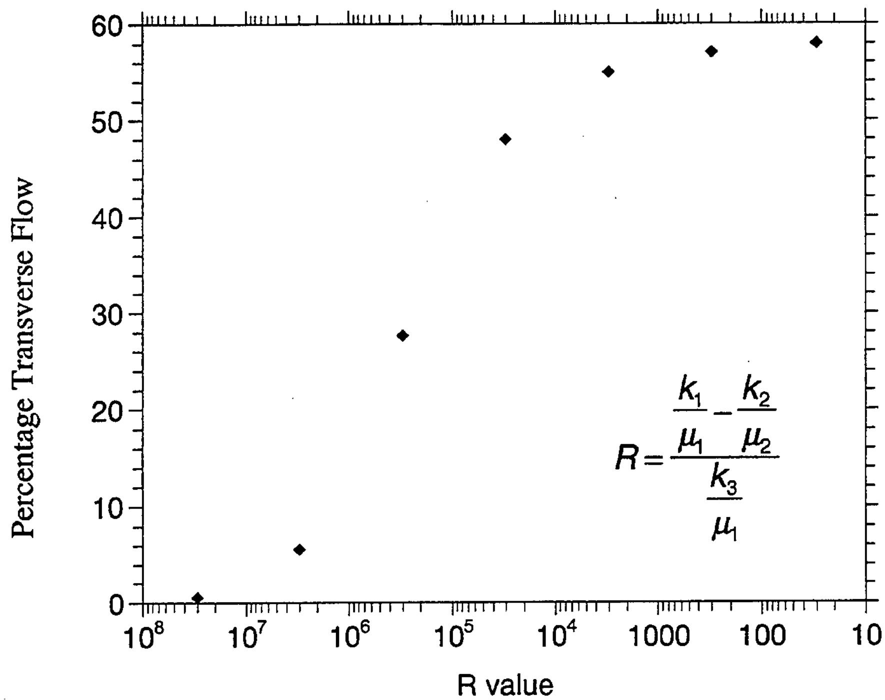

Figure 7. Percentage of Cross Flow With Respect to Half the Mold Volume as a Function of the Ratio of In-Plane to Transverse Permeability.

The results from this parametric study show that it is extremely difficult to control the transverse flow. The only case in which it was possible to limit the transverse flow to less then 1% was by using an extremely small transverse permeability. In practice, it is very difficult to find a separation layer with a transverse permeability that is approximately 7 orders of magnitude smaller than the in-plane permeability of a reinforcing preform. Consequently, this parametric study supports our experimental work showing that an impermeable layer is required.

5. Part Length Considerations

The 1-D model also emphasized the effect of the part length on the transverse flow. Figure 4 showed that the amount of transverse flow eventually levels off, but this only happens after considerably long distances. The parametric study was conducted by varying the length of the part while maintaining all other parameters constant. Figure 8 shows the total transverse flow as a function of time. Time has been normalized with respect to the total fill time of each mold.

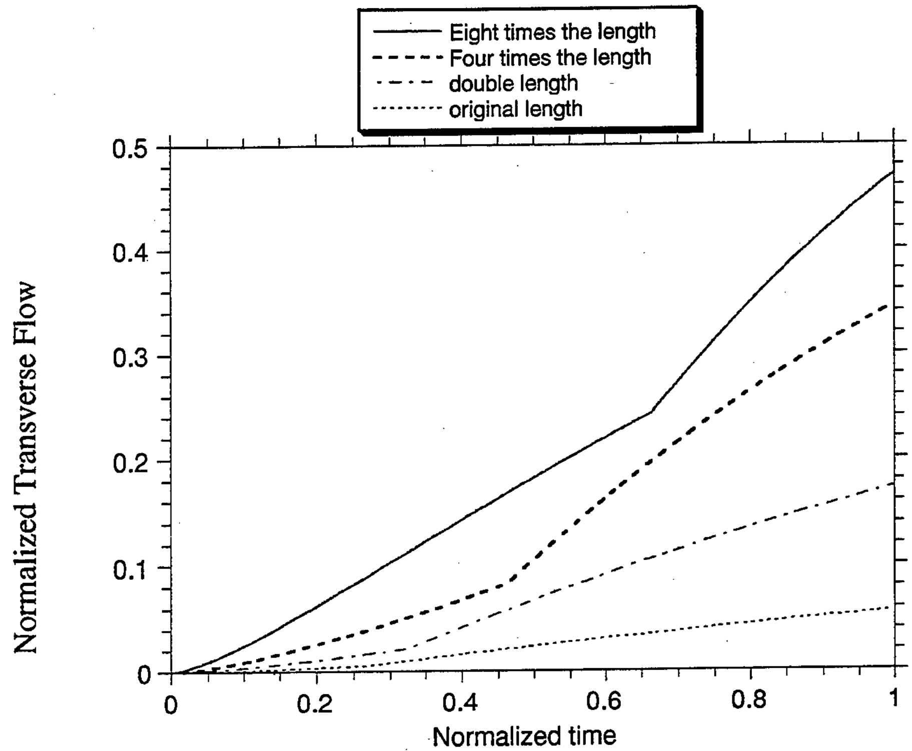

Figure 8. Effect of Part Length on Total Percentage of Transverse Flow. Transverse Flow Is Normalized With Respect to Half the Mold Size. Time Is Normalized With Respect to Total Filling Time.

The percentage cross flow is computed with respect to half of the mold volume. Clearly, the amount of cross flow increases with increasing mold size. This is also reflected in Figure 9, which suggests that the transverse flow does not increase linearly but, rather, eventually levels off. This behavior is expected because it was also observed in the 1-D model.

6. Conclusions

The goal of understanding the parameters that govern the flow in CIRTM was met using the 1-D model. In CIRTM, as the resins fill the two layers in the mold, two pressure profiles develop. These profiles are determined by the ratio of the permeability of the preform to the viscosity of the resin. Since, in the majority of cases the two ratios are different, two different pressure profiles develop in the top and bottom layer. When this occurs, a pressure gradient

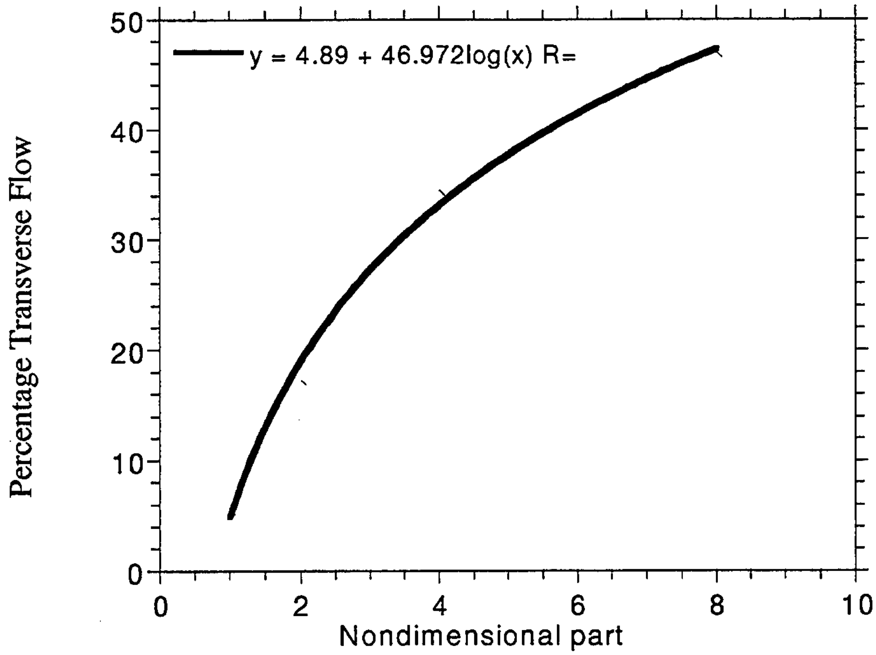

Figure 9. Percentage of Transverse Flow as a Function of Part Length. Log Curve Fit Is Shown.

forms in the transverse direction and drives the transverse flow. The model also showed that the amount of transverse flow increases rapidly until it reaches a steady-state point. All of the results from this model qualitatively matched the ones from the finite element model.

The finite element model allowed measuring the amount of transverse flow and determining the importance of the transverse permeability and the effect of part length on the transverse flow. The model also relaxed the assumption of linear pressure profile in each half of the mold. It showed that a transverse permeability 7 orders of magnitude smaller then the in-plane permeability is needed to reduce the transverse flow to less then 1% of half the mold size. In practice, it is almost impossible to find a preform material with this property. Additionally, the finite element code proved that increasing the part length and, therefore, the distance that the resin must travel, increases the amount of transverse flow. As in the 1-D model, the amount of transverse flow seems to eventually reach a steady-state situation but only after a significant amount of mixing has occurred.

Overall, the results from the two models agree qualitatively and also agree with preliminary experiments conducted in the lab. In order to use the co-injection process for large structures, it is necessary to use a completely impermeable separation layer. This will completely eliminate transverse flow. For smaller scale applications, the results presented in this study provide useful guidance for selection of resin and preforms to minimize transverse flow.

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13. ABSTRACT *(Maximum 200 words)*

A co-injection resin transfer molding (CIRTM) process has been developed at the U.S. Army Research Laboratory (ARL) in collaboration with the University of Delaware. It enables two or more resins to be simultaneously injected into a mold filled with a stationary fiber preform. This process allows for the manufacturing of cocured multilayer multiresin structures in a single processing step. A separation layer is used to provide resin compatibility during cure and to control resin mixing. In this study, scaling issues relating the role of transverse permeability in resin mixing are investigated. This report presents two different approaches taken to understand the causes of transverse flow and to quantify the amount of transverse flow. The first approach is a one-dimensional (1-D) model, which explains the important parameters that govern the flow in CIRTM. The second approach is based on an existing finite element code, which is modified to allow for the injection of multiple resins. The total amount of transverse flow was quantified using the finite element code. This research shows that he CIRTM process requires a totally impermeable separation layer if CIRTM is used to manufacture large parts and/or if the resins injected have significantly different viscosities.

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